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Dissertation Organization

This dissertation is divided into two main subjects: 1. soil testing methodology and 2. soil test interpretation. This dissertation is organized into four chapters. The first chapter is a general introduction and review of the literature relevant to this dissertation. The second chapter is a manuscript of the soil testing methodology experiments entitled, 'Calcium carbonate affects the determination of exchangeable cations and cation exchange capacity.' The third chapter is a manuscript of the greenhouse experiments evaluating the basic cation saturation ratio theory of soil test interpretation entitled, 'Basic cation saturation ratio theory applied to sand-based putting greens.' The fourth chapter reviews the overall results and conclusions drawn from both manuscripts.

General Introduction

Soil Testing Methodology

Many golf course greens and sports fields utilize sand-based rootzones for their beneficial physical properties (Snow, 1993). Sand-based root zones are less likely to compact than soil-based rootzones, and they have greater water and air infiltration rates. However, the chemical properties of sand-based rootzones are often less desirable than soil-based rootzones. The water and nutrient holding capacities are greatly reduced compared to soil-based media. The cation exchange capacities (CEC) of sand-based rootzones can vary from less than 1 up to 6 $\text{cmol}_c \cdot \text{kg}^{-1}$ (Christians, 1990). Because of the low nutrient holding capacity and high water infiltration rates, sand-based systems are best fertilized using light and frequent fertilizer applications, often called spoon-feeding. To ensure proper fertilization, turf managers must use every tool available to them, including accurate soil tests to monitor the fertility status of the soil.

Analyzing the plant-available nutrient status of a soil requires using an extractant. Water can be used as a simple extractant. This method is commonly called the saturated paste measurement. It assesses the soluble and readily dissolvable salts fractions of plant-available nutrients in the soil. In this procedure, a small amount of deionized water is added to a soil sample to make a paste or slurry, and then the water is filtered, centrifuged or siphoned off for determination of nutrients. Since this technique analyzes such a small portion of the total plant available nutrients, it is difficult to accurately assess the ability of a soil to supply nutrients for a wide variety of soil types and textures. Moreover, the soluble

and readily dissolvable nutrient fractions are going to vary widely and change rapidly.

Saturated paste measurements are generally not widely used for turfgrass soil analysis.

It is more desirable to assess the nutritional status of the exchangeable fraction of nutrients held on charged sites within the soil. To do this, a chemical extractant must be used to analyze exchangeable cations. Typically, a soil sample is saturated with a solution containing a high concentration of an index cation, like ammonium (NH_4^+) that has a strong affinity for exchange sites. After several equilibrations with the saturating solution, the index cation will replace all the other cations on the exchange sites and they can be collected and measured.

In addition to measuring the plant available nutrients, knowing the CEC of a soil can help in determining the size and frequency of fertilizer applications. This is particularly true on sand-based systems that generally have a low CEC. Two common methods for estimating CEC in soils include performing a double extraction method or using a summation of exchangeable cations to estimate an effective cation exchange capacity, ECEC. The double extraction approach uses two solutions, a saturating solution, followed by an extracting solution. The saturating solution is fairly concentrated with a known index cation (e.g. NH_4^+). The soil sample is saturated several times with the saturating solution replacing all of the exchangeable cations in the soil with the index cation. The second solution, the extracting solution, is a concentrated solution of a second cation that has a greater affinity for the exchange sites than the first saturating cation (e.g. Mg^{2+}). The soil plus index cation is equilibrated several times with the extracting solution. In this example, the Mg^{2+} will displace the NH_4^+ and the NH_4^+ concentration can be measured in the collected extractant. The CEC is calculated by calculating the concentration of the index cation (NH_4^+) and its

total charge per unit of soil. The total charge from the index cation is equal to the exchange capacity of the soil and is reported in moles of charge per weight of soil, typically $\text{cmol}_c \cdot 100\text{g}^{-1}$.

The second approach is to estimate the CEC by adding together all of the extractable cations measured. This technique is known as effective cation exchange capacity (ECEC). The exchangeable cations are measured as describe above, and the charges associated with them are added together to give an estimated total charge capacity for the soil. Unfortunately, many soil test report forms do not differentiate as to whether they are reporting ECEC or CEC, and there can be differences in value between the two methods.

One of the largest problems with the procedures for measuring exchangeable cations and CEC is the dissolution of carbonate and sulfate based soil particles during the soil testing process. Frequently, limestone-based (CaCO_3) sands are used for construction of golf course greens and sports fields. These sands have varying quantities of CaCO_3 and MgCO_3 ranging from 1% to 40% by weight (Christians, 1990) and are, therefore, termed calcareous.

Ammonium acetate (NH_4OAc) pH 7.0 is an industry standard for measuring exchangeable cations, CEC and ECEC. The NH_4OAc pH 7.0 extractant is known to dissolve carbonates and sulfates and is not recommended for analysis of calcareous or gypsiferous soils (Rhoades, 1982; Suarez, 1996, Sumner and Miller, 1996; Normandin et al., 1998; St. John, et al., 2003). Dissolution of soil particles like CaCO_3 will add extra Ca^{2+} ions into the collected soil extract and will overestimate the exchangeable Ca concentrations. If an ECEC is created by summing the exchangeable cations, this dissolution will also inflate the ECEC values. Finally, basic cation saturation percentages and cation equivalent ratios will also be erroneous. Dissolution of calcareous or gypsiferous particles of sand samples from putting

greens or sports fields is going to greatly influence the results compared to soil-based samples that contain much larger clay and organic matter fractions.

The objectives of the first manuscript included in this dissertation are to evaluate different soil testing procedures for analysis of sand based samples from putting greens, and to determine the best possible methods for exchangeable cation and CEC analysis.

Soil Test Interpretation

The second part of this research deals with soil test interpretation, specifically, the Basic Cation Saturation Ratio (BCSR) theory. There are two main methods for interpreting soil test results, sufficiency level of available nutrients (SLAN) and BCSR (Eckert, 1987). The SLAN method utilizes a set of defined concentrations of each nutrient as sufficiency levels. If a soil extractable nutrient concentration is below the sufficiency level, it is highly probable that the crop will respond favorably from fertilizer application. If the soil extractable nutrient concentration is above the sufficiency level, it is said to be adequate for proper growth and yield. The SLAN method interprets soil nutrient status based on the following guidelines. The nutrient is said to be in the 'Low Range' when there is 80-100% chance that applying the nutrient will cause the crop to respond favorably, in the 'Medium Range' when there is a 50% chance for response, but supplement fertilizer applications may be needed in the near future, in the 'High Range' when there is little or no chance for crop response from nutrient application, or in the 'Very High Range' when applying more of that nutrient may reduce growth (Carrow et al., 2004).

The BCSR theory is based upon the belief that there is an ideal ratio of soil nutrients rather than a minimal nutrient concentration that exists for optimal plant growth. This leads

to one of the major problems of the BCSR theory, that even if the exchangeable cations are in the correct proportions, a nutrient deficiency can still be present, thus, limiting growth and yield. A second problem with BCSR is that it tries to apply the ideal ratio to all crops on all soils. Sufficiency levels of SLAN have been determined for many crops by researching each crop on a variety of soil types and are continually being updated with new information as research progresses, whereas the BCSR theory has much less field based research.

The BCSR theory was proposed in the late 1940's by researchers investigating alfalfa growth in New Jersey (Bear et al., 1945; Bear and Toth, 1948; Hunter et al., 1943; Hunter, 1949; Price et al., 1947). They proposed that optimal growth and yield would be achieved when the cations, calcium (Ca), magnesium (Mg), potassium (K), and hydrogen (H) occupied the cation exchange sites in the exact percentages of 65%, 10%, 5% and 20%, respectively. From these saturation percentages, they developed cation equivalent ratios of Ca:Mg 6.5:1, Ca:K 13:1, and Mg:K 2:1. Graham (1959) later expanded the exact saturation percentages to 65-85% Ca, 6-12%Mg, 2-5%K. Graham's ranges of percentages are the current adopted values for the BCSR theory. However, many BCSR interpretations are still done using the precise cation ratios of 6.5:1, 13:1 and 2:1, rather than making interpretations on a range of ratios that could be created from Graham's percentages, Ca:Mg 5.4:1 – 14:1, Ca:K 13:1 – 42.5, and Mg:K 1.2:1 – 6:1.

The BCSR theory has been debated for the last 50 years. Most of the research to date finds that the exact ratio of cations is not overly important, and it is more important that one cation does not exist in such an over-abundant quantity that it limits the uptake of other cations (Stevens, et al., 2005; Abedin et al., 1998; Sartain, 1993; Eckert, 1987; Sartain, 1985;

McLean et al., 1983; Eckert and McLean, 1981; Liebhardt, 1981; Simson et al., 1979). Yet, use of the BSCR theory and questions about its validity still remain.

Recently, the BSCR theory has seen an increase in use, possibly due to specialty fertilizer manufacturers trying to apply the theory to aid in sales of their products. The objectives of the second half of this dissertation are to better understand the BCSR theory and to determine the validity of applying it to sand-based putting greens and athletic fields.

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Calcium Carbonate Affects the Determination of Exchangeable Cations and Cation Exchange Capacity

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Abstract

Some soil testing procedures dissolve calcium carbonate or gypsum, which will cause increased readings of extractable calcium. This dissolution will also increase the estimated cation exchange capacity (ECEC) when the cations are summed together. On soils with large proportions of clay and organic matter, this dissolution problem usually has a small affect on the results, but in the high-sand, low-organic-matter, calcareous root zones used for construction of some putting greens and sports fields, the dissolution of calcium carbonate can greatly influence the results. Raising the pH of the standard 0.5M ammonium acetate (NH₄OAc) extracting solution from pH 7.0 to pH 8.1 reduced the dissolution of CaCO₃ measured by 33%. Measuring the CEC by the double extraction CaCl₂/Mg(NO₃)₂ method produced CEC values that were 87% smaller than the ECEC calculated from NH₄OAc pH 7.0. For measuring exchangeable cations of calcareous or gypsiferous sand samples, the NH₄OAc at pH 8.1 offered the best results along with ease of analysis. Cation exchange capacity determinations of calcareous or gypsiferous sands should be done using a double extraction technique and should not be estimated by calculating an ECEC. Silica sand samples can be analyzed using NH₄OAc pH 7.0 or Mehlich 3 for exchangeable cations and summing of cations for ECEC calculation.

Introduction

Many golf course putting greens and sports fields utilize sand-based rootzones based upon USGA specifications United States Golf Association (USGA) (Snow, 1993). Sand rootzones are chosen for their beneficial physical properties, like good water and air infiltration rates and reduced capacity for compaction. Unfortunately, sand-based rootzones can have some less than desirable chemical properties. These sand rootzones have very low cation exchange capacities (CEC), ranging from 1 to 6 $\text{cmolc}\cdot\text{kg}^{-1}$ (Christians, 1990). The small CEC has a limited ability for holding nutrients; therefore, care must be taken when applying fertilizers to limit the possibility for leaching while maintaining adequate nutrition for growth and aesthetics.

Additionally, many sands used for construction are calcareous. Calcareous soils are created from the weathering of rocks, like limestone (CaCO_3), or shells that contain different forms of carbonates. The solubility of CaCO_3 is affected by pH and carbon dioxide (CO_2) concentrations. Due to the relationship between CaCO_3 , CO_2 , CO_3^{2-} (carbonates) and HCO_3^- (bicarbonates), the soil solution of calcareous sands and soils is usually buffered at approximately pH 8.2. This alkaline pH can limit the availability of several nutrients like phosphorus (P), iron (Fe), and manganese (Mn).

For these reasons, frequent soil testing to assess the nutritional status of sand-based growing media is a necessity. Unfortunately, the soil testing procedures generally used to measure exchangeable cations and CEC may not be providing accurate results. Ammonium acetate (NH_4OAc) pH 7.0 is one method that is frequently used for measuring exchangeable cations and estimating CEC by the summation of the exchangeable cations, called effective cation exchange capacity (ECEC). Because the NH_4OAc pH 7.0 extracting solution has a

near neutral pH, is strongly buffered, and has a relatively high ionic strength, carbonates and gypsiferous particles will dissolve, and it is not recommended for calcareous soils (Rhoades, 1982; Sumner and Miller, 1996; Normandin et al., 1998; St. John, et al., 2003). It is important to note, that the exchangeable cations measured from the NH_4OAc pH 7.0 procedure are commonly added together to give an ECEC. But, if the procedure is dissolving CaCO_3 , MgCO_3 , or other particles containing cations, the ECEC will be overestimated. This is especially important when dealing with sand-based greens. On soils with large proportions of clay and organic matter, this dissolution problem usually has a small affect on the results, but in the high-sand, low-organic-matter, calcareous root zones used for turf, the dissolution of calcium carbonate can greatly influence the results. Any errors due to dissolution of carbonates are going to greatly change the ECEC, exchangeable cations, cation ratios, and the interpretation of the results needed for developing a fertility program.

There are two ways to approach this problem of dissolution, limit the dissolution or make corrections for it. Some common ways to limit or prevent dissolution include raising the pH and/or lowering the ionic strength of the extracting solution. One correction-type procedure, NH_4Cl method (Suarez, 1996), measures the carbonate and sulphate concentration in the soil extracts and relates those concentrations to dissolved CaCO_3 and CaSO_4 , respectively (Suarez, 1996). These amounts can then be subtracted from the total exchangeable Ca measured.

Methods have been developed for measuring exchangeable cations and CEC in calcareous or gypsiferous soils (Papanicolaou, 1974; Rhoades, 1982; Suarez, 1996; Sumner and Miller, 1996; Pierce and Morris, 2004), but they have not been adopted by routine testing laboratories due to cost or labor restrictions. The objectives of this research were to

demonstrate the variability of exchangeable cation and CEC measurements of standard soil testing procedures by quantifying the effects of calcium carbonate on different soil testing procedures, and to make recommendations for soil testing methodology for calcareous or gypsiferous sand samples from turfgrass areas.

Materials and Methods

An initial comparison of methods for exchangeable cations was performed on a collection of 19 different sand/soil samples collected from Ames, IA. The samples ranged from a USGA sand-based green to Nicollet (fine-loamy, mixed, mesic Aquic Hapludoll) to a 1/3 peat, 1/3 sand and 1/3 Nicollet soil. The samples were analyzed using 0.5M NH₄OAc pH 7.0 and 8.1, 0.5M NH₄Cl and Mehlich 3 according the procedures listed below.

A set of ‘manufactured’ sand samples was created for quantifying the effect of CaCO₃ on different analysis techniques for measuring exchangeable cations, and CEC. Twenty four sand samples were created in the laboratory using a silica sand base (Unimin Corporation, Portage, WI) and adding increasing percentages of either a lab-grade CaCO₃ (Fisher Scientific C64-500 CAS 471-34-1) or a local calcareous sand (Table 1). The CaCO₃ percentage of the calcareous sand was determined gravimetrically (Loeppert, R.H. and D.L. Suarez, 1996). The calcareous sand had 11% CaCO₃.

The extraction techniques for exchangeable cations, CEC and ECEC performed in this study are listed in Tables 2 and 3. The ammonium acetate (NH₄OAc) pH 7.0 and 8.1 followed similar procedures. The extraction solutions were prepared according to referenced methods by Suarez (1996). A 5g sand/amendment sample was weighed into a 50 ml polypropylene centrifuge tube to which 33 ml of extracting solution was added. The tubes

were then shaken for 30 min, centrifuged for 10 min, and then the supernatant was filtered through a Whatman 42 paper into a 100 ml volumetric flask. The process was repeated 2 more times, and the extractant was brought to 100 ml volume. Exchangeable cations were determined by using inductively coupled argon plasma emission (ICAP) techniques (Jones, 1977; Munter and Grande, 1981) on an IRIS/AP Duo (Thermo Jarell-Ash, Franklin, MA) with a charged injection device (Epperson et al., 1988).

The ammonium chloride (NH_4Cl) method is very similar to the NH_4OAc methods. The NH_4Cl solution was produced according to Suarez (1996). Then, extraction of the exchangeable cations followed the same procedure as the NH_4OAc methods, above. Five grams of soil was equilibrated 3 times with NH_4Cl solution, centrifuged, and filtered for a final volume of 100 ml. Extractable cations were measured from the collected extractant. After which, sub-samples of the extractant were analyzed for alkalinity and sulfate concentration determinations. The sum of the alkalinity and sulfate can be related to the Ca dissolved from CaCO_3 and CaSO_4 , respectively, and is subtracted from the exchangeable Ca concentration.

The Mehlich 3 solutions were produced according to the procedure detailed by Mehlich (1984). A 2.5 g sand/amendment sample was weighed into a 50 ml polypropylene centrifuge tube to which 25 ml of Mehlich 3 extracting solution was added. The tubes were shaken for 15 min, centrifuged for 5 min and filtered through a Whatman 42 paper. Exchangeable cations were determined by ICAP analysis.

The saturated paste/water extraction procedure was followed according to the method published in the Soil Analysis Handbook of Reference Methods (Soil and Plant Analysis Council, 2000). A 5 g sand/amendment sample was weighed into a 50 ml polypropylene

tube to which 25 ml of DI water was added. The tube was then shaken for 30 min, allowed to rest for 10 min and then filtered through a Whatman 42 paper. Cations were analyzed by ICAP.

The exchangeable cations determined from the NH_4OAc pH 7.0 and 8.1, NH_4Cl , and Mehlich 3 extractions were summed to create ECEC values. Two more procedures were used for a more direct CEC measurement, $\text{CaCl}_2/\text{Mg}(\text{NO}_3)_2$ (Sumner and Miller, 1996) and $\text{NaOAc-NaCl}/\text{Mg}(\text{NO}_3)_2$ (Rhoades, 1982).

The procedure described by Sumner and Miller was performed as follows: a 5 g sample of the sand/amendment was placed into a 50 ml polypropylene centrifuge tube to which 33 ml of the 0.2M CaCl_2 - 0.0125M CaSO_4 saturating solution was added. The tubes were shaken for 15 min, centrifuged for 5 min, and then the supernatant was discarded. This process was repeated 2 more times. The tubes were then filled with 33 ml of 0.2M $\text{Mg}(\text{NO}_3)_2$, shaken for 15 min, centrifuged for 5 min, and the supernatant was filtered through a Whatman 42 paper into a 100 ml volumetric flask. This process was repeated 2 more times and the final extractant was brought to 100 ml volume. Calcium and Mg were determined from the extractant by ICAP analysis.

The $\text{NaOAc-NaCl}/\text{Mg}(\text{NO}_3)_2$ (Rhoades, 1982) procedure consisted of placing 5 g of the sand/amendment sample into a 50 ml polypropylene centrifuge tube. Then 33 ml of the 0.4M NaOAc – 0.1M NaCl , 60% ethanol, pH 8.2 saturating solution was added. The tubes were placed on the shaker for 15 min and centrifuged for 5 min. The supernatant was discarded, and the process was repeated 2 more times. After which, 33 ml of 0.5M $\text{Mg}(\text{NO}_3)_2$ extracting solution was added. The tubes were shaken for 15 min, centrifuged for 5min, and filtered through a Whatman 42 paper into a 100 ml volumetric flask, and repeated

2 more times. The resulting extractant was brought to volume and Na and Mg were determined by ICAP.

Results

Raising the pH of the ammonium acetate solution from 7.0 to 8.1 reduced the Ca concentration of the soil extracts an average of 33% (Table 4). The NH_4Cl procedure measured an average 16% less Ca than the NH_4OAc pH 7.0 extraction procedure (Table 4).

The affects of CaCO_3 on the 5 different soil test techniques for measuring exchangeable cations are presented in Figure 1. Much more Ca was dissolved when using reagent grade CaCO_3 compared to using calcareous sand. When using reagent grade CaCO_3 , the dissolution of CaCO_3 reached a plateau for each extraction technique. Calcium concentration from Mehlich 3 leveled off between 10-15% CaCO_3 content. Calcium concentrations from the NH_4OAc pH 8.1 and NH_4Cl methods leveled off around 0.5% CaCO_3 , and from NH_4OAc pH 7 leveled off around 2% CaCO_3 . The different techniques affect the solubility of CaCO_3 in different magnitudes. The extractable Ca concentrations from sands amended with reagent CaCO_3 were nearly double compared with Ca concentrations from sands amended with calcareous sand. The extractable Ca concentrations from the silica + calcareous sand did not reach a plateau like the silica sand + reagent CaCO_3 .

When measuring the CEC by double extraction ($\text{CaCl}_2/\text{MgNO}_3$ and $\text{NaOAc-NaCl}/\text{Mg}(\text{NO}_3)_2$), the CEC ranged from 1.1 to 2.0 $\text{cmolc}\cdot 100\text{g}^{-1}$ and 1.6 to 3.0 $\text{cmolc}\cdot 100\text{g}^{-1}$, respectively (Figure 2). ECEC values created by summing the exchangeable cations ranged from 0.3 to 23.6 $\text{cmolc}\cdot 100\text{g}^{-1}$ for NH_4OAc pH 7.0, 0.1 to 10.6 $\text{cmolc}\cdot 100\text{g}^{-1}$ for NH_4OAc pH 8.1, 0.1 to 10.2 $\text{cmolc}\cdot 100\text{g}^{-1}$ for NH_4Cl , and 0.1 to 124.1 $\text{cmolc}\cdot 100\text{g}^{-1}$ for Mehlich 3.

Discussion

Not as much Ca was dissolved when using sand as the CaCO_3 source compared to using reagent grade CaCO_3 . This is to be expected and is attributed to particle size and purity. The lab grade CaCO_3 was a finely ground pure powder whereas the sand had a much larger particle size and the individual particles of sand-based CaCO_3 probably contained impurities, both of which are going to cause a reduced dissolution rate.

When analyzing silica sand + reagent CaCO_3 the Ca concentration reached a plateau that was unique for the different extraction chemicals.

The Mehlich 3 extractant measured similar Ca levels compared to NH_4OAc pH 7.0 when using silica sand + calcareous sand, but when analyzing silica sand + reagent CaCO_3 , the extractable Ca levels rose nearly 5 times higher than any other extractant. Mehlich 3 should not be used to measure exchangeable cations of calcareous sand samples. Raising the pH of the industry standard NH_4OAc pH 7.0 procedure to a pH of 8.1 to limit CaCO_3 dissolution is recommended for arid soils (Suarez, 1996). The NH_4Cl method (Suarez, 1996), which makes corrections for the amount of dissolution, had reduced concentrations exchangeable calcium compared to NH_4OAc pH 7.0 and Mehlich 3. But, due to the labor involved with several post extraction procedures needed to make the alkalinity and sulfate corrections, it is doubtful that many routine soil testing laboratories will adopt this procedure. Based on the results in this paper, measuring exchangeable basic cations of calcareous or gypsiferous sand-based samples should be done by NH_4OAc at pH 8.1, because of it reduces CaCO_3 dissolution and its ease of use.

The affect of CaCO_3 dissolution was nearly negligible when using a double extraction technique like $\text{CaCl}_2/\text{MgNO}_3$ or $\text{NaOAc-NaCl}/\text{Mg}(\text{NO}_3)_2$ compared to creating an ECEC by summation of extractable cations. Therefore, to achieve accurate CEC measurements of calcareous or gypsiferous sand-based samples only double extracting techniques should be used and ECEC estimates should be avoided.

Based on this research, exchangeable cations and CEC should be measured separately for calcareous or gypsiferous sand samples. Pure silica sand samples can potentially be analyzed with any procedure studied in this research. But, if the silica sand sample has a possibility of containing any carbonates or sulfates, then NH_4OAc pH 8.1 should be used to measure exchangeable cations and a double extraction technique for measuring CEC.

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Table 1. List of how sands were created in the laboratory to measure the effects of CaCO_3 on different soil testing procedures.

Treatment	% Silica Sand	% Amendment	Type of Amendment	% CaCO_3
1	100	0	Lab-Grade	0
2	99	0.5	Lab-Grade	0.5
3	98	1	Lab-Grade	1
4	97	2	Lab-Grade	2
5	96	3	Lab-Grade	3
6	95	4	Lab-Grade	4
7	90	5	Lab-Grade	5
8	95	10	Lab-Grade	10
9	80	15	Lab-Grade	15
10	75	20	Lab-Grade	20
11	70	25	Lab-Grade	25
12	60	30	Lab-Grade	30
13	99	0.5	Calcareous Sand	0.055
14	98	1	Calcareous Sand	0.11
15	97	2	Calcareous Sand	0.22
16	96	3	Calcareous Sand	0.33
17	95	4	Calcareous Sand	0.44
18	90	5	Calcareous Sand	0.55
19	95	10	Calcareous Sand	1.1
20	80	15	Calcareous Sand	1.65
21	75	20	Calcareous Sand	2.2
22	70	25	Calcareous Sand	2.75
23	60	30	Calcareous Sand	3.3
24	0	100	Calcareous Sand	11

Table 2. List of methods used to determine exchangeable cations.

Method	Reference
1 0.5M Ammonium Acetate pH 7.0 (NH ₄ OAc pH 7)	Suarez, 1996
2 0.5M Ammonium Acetate pH 8.1 (NH ₄ OAc pH 8.1)	Suarez, 1996
3 0.5M Ammonium Chloride pH 7.0 (NH ₄ Cl)	Suarez, 1996
4 Mehlich 3	Mehlich, 1984
5 Saturated Paste – Water Extract	Soil and Plant Analysis Council, 2000

Table 3. List of methods used to determine cation exchange capacity (CEC). Summation of cations to calculate effective cation exchange capacity (ECEC).

Method	Reference
1 0.2M CaCl ₂ / 0.5M Mg(NO ₃) ₂	Sumner and Miller, 1996
2 0.5M NaOAc – 0.1M NaCl / 0.5M Mg(NO ₃) ₂	Rhoades, 1982
3 Summation of Exchangeable Cations from NH ₄ OAc pH 7	Suarez, 1996
4 Summation of Exchangeable Cations from NH ₄ OAc pH 8.1	Suarez, 1996
5 Summation of Exchangeable Cations from NH ₄ Cl	Suarez, 1996
6 Summation of Exchangeable Cations from Mehlich 3	Mehlich, 1984

Table 4. Average Ca concentration from 19 soil and sand samples collected from Ames, IA according to 4 different soil extracting techniques.

Method	Ca mg/kg
Mehlich 3	3100 a†
0.5M NH₄OAc pH 7.0	2774 ab
0.5M NH₄Cl	2328 c
0.5M NH₄OAc pH 8.1	1853 d

† Means with the same letter are not significantly different according to Tukey's multiple comparison error rate. ($p \leq 0.05$)

Figure 1: Exchangeable Ca measured from different soil extraction methods of sand samples mixed with increasing volumes of CaCO_3 from either reagent-grade CaCO_3 (top) or calcareous sand (bottom).

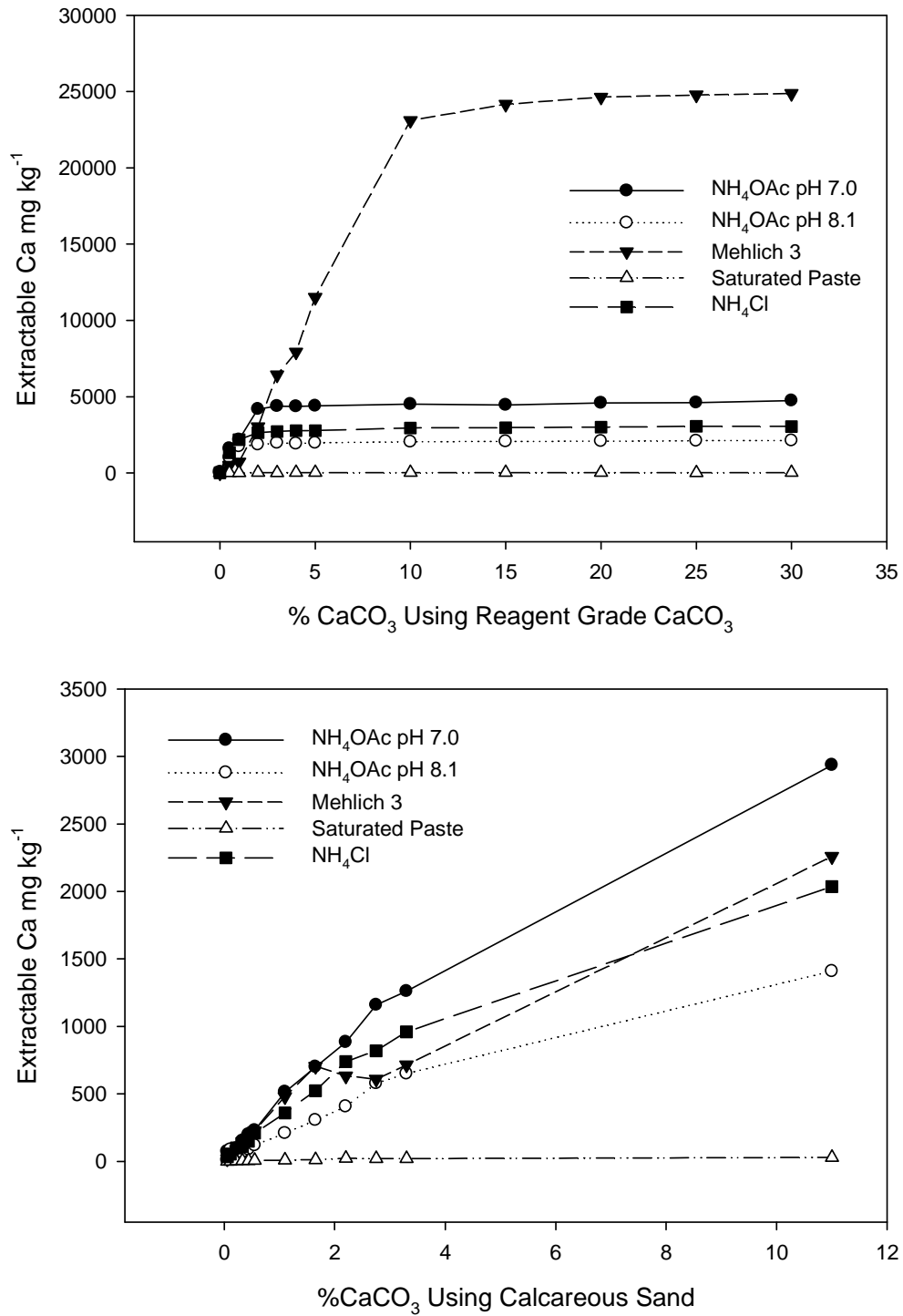
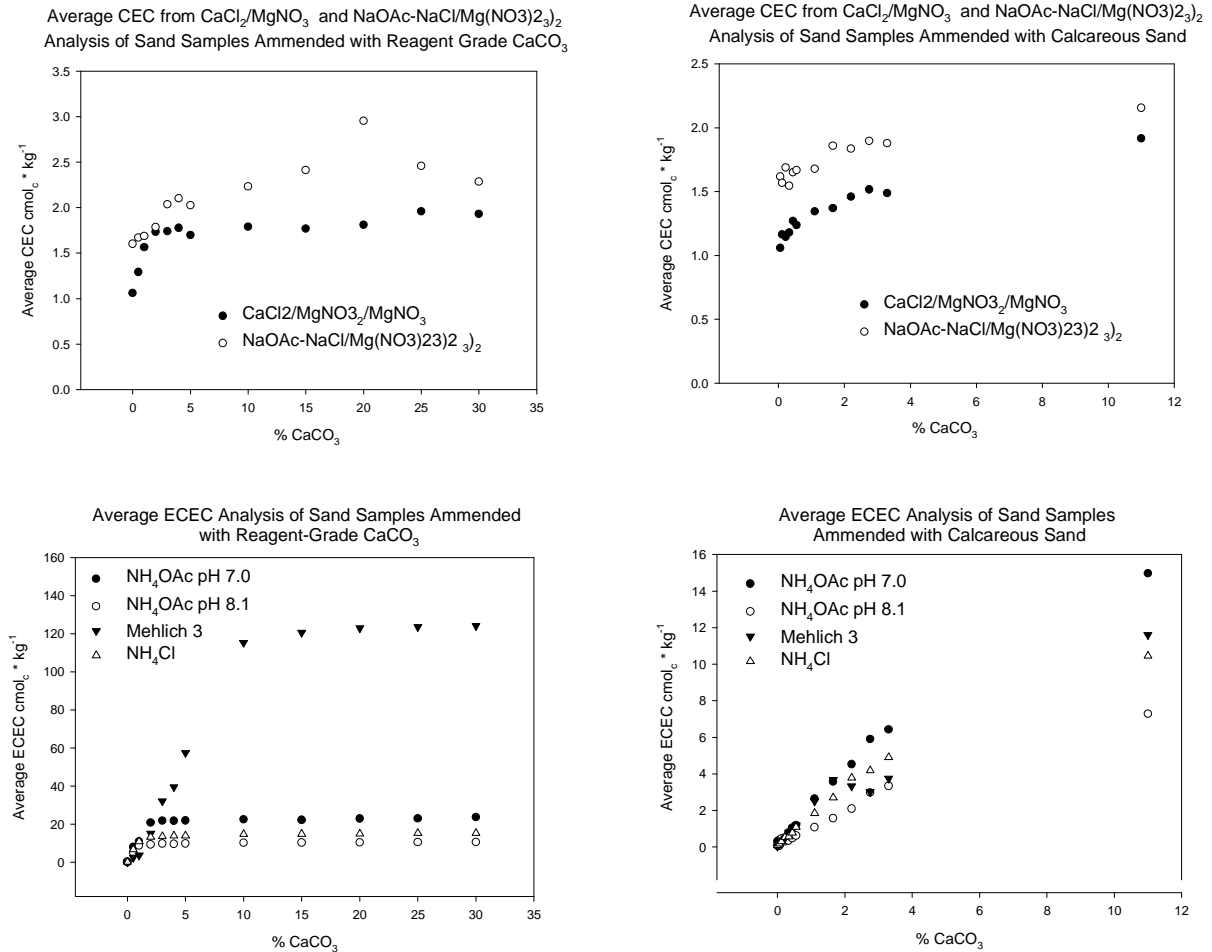


Figure 2: Plots of the average CEC (top) from $\text{CaCl}_2/\text{MgNO}_3$ and $\text{NaOAc-NaCl/Mg}(\text{NO}_3)_2$ and ECEC (bottom) from NH_4OAc pH 7.0, NH_4OAc pH 8.1, Mehlich 3, and NH_4Cl analyses of sand samples with increasing CaCO_3 levels from reagent-grade CaCO_3 (left) and from calcareous sand (right).



Basic Cation Saturation Ratio Theory Applied to Sand-Based Putting Greens

R.A. St. John, N.E. Christians, H.G. Taber

Abstract

The basic cation saturation ratio theory of soil test interpretation states that calcium (Ca), magnesium (Mg), and potassium (K) should be present on the cation exchange sites in the soil in the following percentages, 65 – 85%, 6 – 12% and 1 – 5%, respectively. Golf course putting greens are often constructed utilizing a sand-based rootzone. Since sands generally have a low cation exchange capacity (CEC), it is possible that the Ca, Mg, and K cations can occupy the correct ratios within the rootzone, and still be deficient. Also, the validity of these cation ratios has not been thoroughly evaluated for creeping bentgrass on low CEC soil media. The objective of this research was to evaluate the BCSR theory for sand based greens. Twenty eight cation treatments of widely varying cation ratios were applied to 'Penncross' creeping bentgrass (*Agrostis stolonifera* L.) established on either calcareous or silica sand. There were no differences in quality or clipping yield among the 28 treatments. The bentgrass tolerated a wide range of applied cation ratios. Samples from the silica sand pots had high K saturation percentages, >28%, but leaf and soil extractable K concentrations were very low, <21 g·kg⁻¹ and <1.6 mg·kg⁻¹, respectively. Dissolution of CaCO₃ from calcareous sand samples resulted in Ca saturations percentages all greater than 95%. Additionally, the silica sand samples had such a small CEC that calculated cation saturation percentages and ratios gave misleading results. The Ca:K ratios of silica sand ranged from 1:1 to 2:1, whereas, according to the BCSR theory, they should be 13:1 and would call for a Ca application to correct the ratio. However, leaf Ca concentrations from silica sand samples averaged 12 g·kg⁻¹ and leaf K concentrations 8.7 g·kg⁻¹, which according to tissue sufficiency

levels, indicates high leaf Ca and deficient leaf K, and increased K fertilization is needed. Low CEC sands result in widely varying cation saturation ratios that may lead to erroneous interpretations of soil test results. It is recommended that the results of BCSR soil testing not be used as the final determining factor in developing fertility systems for sand-based golf course greens.

Introduction

There are two main concepts of soil test interpretation. They are the sufficiency level of available nutrients (SLAN) and the basic cation saturation ratio (BCSR). The SLAN concept states that there are “definable levels of individual nutrients in the soil below which crops will respond to added fertilizers with some probability and above which they likely will not respond” (Eckert, 1987).

The BCSR theory states that optimal growth occurs when calcium (Ca), magnesium (Mg), and potassium (K) exist in an ideal ratio. The original theory by Bear and Toth (1948) stated that the cations must occupy the cation exchange sites in the following percentages, 65% Ca, 10% Mg, 5% K, and 20% H. From these percentages, ideal cation equivalent ratios can be created, Ca:Mg 6.5:1, Ca:K 13:1, Ca:H 3.25:1, and Mg:K 2:1 (Bear and Toth, 1948). Graham (1959) further broadened the theory to include a range of percentages, 65-85% Ca, 6-12% Mg, 2-5% K. Current recommendations by many professional soil testing laboratories utilize Graham’s range of percentages, but there are still many laboratories that base their recommendations on Bear’s exact cation equivalent ratios. This is currently a problem in the turfgrass industry, where interpretations using Bear’s exact cation equivalent ratios are used in the marketing of fertilizer products. A range of cation equivalent ratios can

be developed using Graham's range of percentages that may provide a better estimate of the soil's ability to supply elements to the plant (Table 1).

The validity of the BCSR theory has been debated extensively since its development. Many studies have shown that crops can grow in soils that have cation ratios outside the 'ideal soil' ratios of the BCSR theory. Sartain (1993) concluded that 'Tifway' bermudagrass (*Cynodon dactylon* (L.) Pers. x *Cynodon transvaalensis* Burt Davy) and 'Pennant' perennial ryegrass (*Lolium perenne* L.) did not require a precise soil Ca to Mg ratio. The growth rate of bermudagrass was not affected even in the presence of a 100 to 1 soil extractable Ca to Mg ratio, (Sartain, 1985). In a study of cotton in Missouri, soil Ca:Mg ratios ranging from 2.5:1 to 7.6:1 had no affect on cotton quality or yield (Stevens, et al., 2005). Stevens et al. (2005) went on to state that "the BCSR concept did not show any merit for managing cotton fertility on well-drained Delta soils." The soil in alfalfa field trials in Wisconsin had Ca:Mg ratios of 2.3:1 to 8.3:1 without any impact on alfalfa yield (Simson et al., 1979).

From their work, Eckert and McLean (1981) stated that the balance of basic cations was only important when one element became deficient due to an excess of other cations, and that there is no ideal basic cation saturation ratio for all crops. McLean et al. (1983) went on to state, "the results strongly suggest that for maximum crop yield, emphasis should be placed on providing sufficient, but non-excessive levels of each basic cation rather than attempting to attain a favorable BCSR which evidently does not exist."

The BCSR theory tries to apply ideal ratios to all crops on all soils, whereas the SLAN concept uses different sufficiency levels for different crops and soil types. These SLAN levels have been created from many decades of research on all kinds of crops on many

kinds of soil, whereas the BCSR theory is applied to all soils and crops based on relatively little research.

Specialty fertilizer dealers have shown a recent interest in applying the BCSR theory to a wide range of crops, including turfgrass to aid in sales of their products. Additionally, many commercial soil testing facilities use the BCSR theory for fertilizer recommendations (McLean, 1977).

The BCSR has another limitation. It is possible that even if a soil contains exchangeable cations in the correct proportions according to the BCSR theory, a nutrient deficiency can still exist. This is particularly true in low cation exchange capacity (CEC) soils, such as those found in golf course greens and sports fields, where elements like K can occupy a high percentage of the CEC sites but may still be deficient. The BCSR theory is further complicated when the rootzone media is calcareous or gypsiferous. Many times the soil testing chemical will dissolve CaCO_3 or CaSO_4 particles and over-estimate exchangeable cations and thereby CEC. Therefore, more work needs to be done to determine the usefulness of the BCSR theory on sand-based turfgrass systems.

The objective of this research was to determine if the BCSR theory applies to creeping bentgrass established on either calcareous or silica sand-based rootzones.

Materials and Methods

The study was conducted as two repeated greenhouse experiments. 'Penncross' creeping bentgrass (*Agrostis stolonifera* L.) was established from seed on round pots with a 15 cm diameter and 15 cm depth. Pots were either filled with calcareous sand or silica sand. Half of the pots were filled with a calcareous sand that had a CEC of $1.9 \text{ cmol}_c \cdot 100 \text{ g}^{-1}$ and

11% CaCO_3 . The other half of the pots were filled with a silica sand from Unimin Corporation, Portage, WI that had a CEC of $1.0 \text{ cmol}_c \cdot 100 \text{ g}^{-1}$. All plants were allowed to grow for 12 weeks before treatment application began.

During the first six weeks of the 12 week grown-in period, grasses grown on silica sand were fertilized with a complete nutrient solution that included Ca, Mg, and K (Pellet and Roberts, 1963). Grasses grown on calcareous sand, received nitrogen (N) and phosphorus (P) at $1.2 \text{ g} \cdot \text{m}^{-2} \cdot \text{week}^{-1}$ and $0.2 \text{ g} \cdot \text{m}^{-2} \cdot \text{week}^{-1}$ during the first six weeks of the grow-in period. During the second 6 weeks of the 12 week grow-in period, all grasses were fertilized with N and P only at levels of $1.2 \text{ g} \cdot \text{m}^{-2} \cdot \text{week}^{-1}$ and $0.2 \text{ g} \cdot \text{m}^{-2} \cdot \text{week}^{-1}$, respectively using ammonium nitrate and phosphoric acid. After the twelve week grow-in period, treatment application and data collection began and continued for another 12 weeks.

A mixtures design was employed to measure different ratios of Ca, Mg, K, and H. Twenty eight treatments were chosen (Table 2). A mixture design is a set of treatments chosen specifically to provide good estimates of the effects of replacing one component with another and to provide a good estimate of the treatment producing the best response. A mixture design provides a statistically reasonable way to understand effects of changing proportions, when the proportions sum to 100%. Figure 1 has two graphical representations of the treatments used in this study compared to the 'ideal soil' according to the BCSR theory. The black area represents a region defined by soils that have cations saturating the exchange sites at 65-85% Ca, 6-12% Mg, and 2-5% K.

Cation nutrient solutions were made using CaCl_2 , MgCl_2 , KCl and HCl . The total level of cations in the nutrient solution was $10 \text{ meq} \cdot \text{L}^{-1}$. This nutrient concentration was chosen based upon concentrations of other complete nutrient solutions (Pellet and Roberts,

1963) and to apply 1/6 of the total exchange capacity per week of one pot of calcareous sand. Table 2 shows the concentration of each element found in each nutrient solution. The solutions were applied weekly on Mondays by applying 100 ml of the appropriate nutrient solution to the corresponding pot. There were 2 sand types and 3 replications of each treatment, 28 treatments, which equals 168 pots of grass for each of the two experiments, and 336 pots combined total.

The pots of grass were grown in a greenhouse under high-pressure sodium lamps with a 14-hour photoperiod and a daily high and low average of 27 °C and 23 °C, respectively. Grasses were mowed twice a week at a height of 10 mm. Quality ratings were taken bi-weekly on Wednesdays and were based on a scale of 9 to 1, with 9 = best quality, 6 = lowest acceptable quality, and 1 = worst quality.

Clippings were also collected bi-weekly on Wednesdays and were dried at 67 °C for 6 days, weighed, and ground in a Wiley mill to pass through a 40-mesh screen. After dry ashing at 490 °C and digesting in aqua-regia, leaf tissue nutrient concentrations were determined by using inductively coupled argon plasma emission (ICAP) techniques (Jones, 1977; Munter and Grande, 1981) on an IRIS/AP Duo (Thermo Jarell-Ash, Franklin, MA) with a charged injection device (Epperson et al., 1988).

Nitrogen was applied weekly on Fridays at $1.2 \text{ g N} \cdot \text{m}^{-2} \cdot \text{week}^{-1}$ using ammonium nitrate. Phosphorus was applied at 3, 6 and 9 weeks at a rate of $0.2 \text{ g P} \cdot \text{m}^{-2}$ using phosphoric acid.

Soil samples were collected 3 times, at the beginning, in the middle and at the end of each experiment. Samples were collected by removing approximately 30 g of sand from the 7 cm depth. Exchangeable Ca, Mg, and K were determined using 0.5M ammonium chloride

(NH₄Cl) pH 7.0 (Suarez, 1996). Cation exchange capacity was estimated by summing the exchangeable cations to calculate the effective cation exchange capacity (ECEC) (Chapman, 1965). Cation ratios and saturation percentages were created from the exchangeable cations and ECEC values.

Repeated measurements of quality, clipping weight, leaf nutrient concentration, and soil nutrient concentration were collected throughout each 12 week experiment. Data were analyzed using the MIXED procedure of the Statistical Analysis Software (SAS Institute, Cary, NC). Contrasts were made between each treatment and an average of the nine treatments that fell within the 'ideal soil' range of the BCSR theory.

Results

There were no differences among quality ratings or clipping weights for grasses grown on either calcareous or silica sand in spite of the widely varying range of Ca, Mg and K. The leaf Ca concentration increased with increasing Ca application (Tables 3 and 4). Across both sands, the leaf Ca concentration ranged from 7.5 – 17.5 g·kg⁻¹ and all grasses had leaf Ca concentrations well above the sufficiency levels reported by Mills and Jones (1996) for creeping bentgrass leaves. Leaf Ca concentration was less than the average leaf Ca of grasses from the 9 'ideal soil' treatments, when the Ca treatment level was less than 40%, with the exception of grasses receiving treatments 5 and 26 (Table 4). Leaf Mg concentration data are presented separated by date and sand due to higher order interactions of date and sand type (Table 5). Across both sands, leaf Mg concentration ranged from 1.8 – 5.2 g·kg⁻¹ (Table 6). On some dates, the leaf Mg concentration differed from the average leaf Mg concentration of grasses from the nine 'ideal soil' treatments. Generally, the differences

occurred when the Mg treatment level was less than 5% applied to both sands (Table 6). Differences also occurred in grasses grown on calcareous sand samples when the Mg treatment level was greater than 80% and in silica samples when the Mg treatment level was greater than 40% (Table 6). Leaf Mg concentrations were normal to above normal of those predicted by Mills and Jones (1996) (Table 6). Across both sands, leaf K concentrations ranged from 3.87 – 21.34 g·kg⁻¹ (Tables 7 and 8). Leaf K concentrations of grasses grown on silica sand were deficient in all treatments that received treatment K percentages of 26% and lower (Table 8). When the applied K treatment level was less than 47%, leaf K concentrations of grasses grown on calcareous sand were deficient according to sufficiency levels by Mills and Jones (1996) (Table 8).

The cation saturation percentages differed greatly between the two sands (Table 9). Samples from silica sand pots had highly variable cation saturation percentages and very high K saturation percentages ranging from 26% to 73% (Table 9). Samples from the calcareous sand pots had very high but consistent Ca saturation percentages ranging from 95 to 98%. Cation ratios also differed greatly between the two sand types (Table 10). The Ca:Mg and Ca:K ratios for samples from calcareous sands were high and ranged from 22:1 up to 53:1 Ca:Mg and from 64:1 up to 401:1 Ca:K. (Table 10). Concentrations of soil extractable calcium and potassium were very low for samples taken from silica sand pots < 9 mg·kg⁻¹ Ca and < 1.6 mg·kg⁻¹ K (Table 11). Extractable Ca concentrations of calcareous sand samples was very high > 1789 mg·kg⁻¹.

Discussion

St. John et al. (2001 and 2003) did not see any increase in leaf Ca concentration in response to Ca fertilization when investigating supplemental applications of Ca to grasses

grown on calcareous sands. It is possible that the increases in Ca in this study were caused by the higher application frequency used here and possibly by these nutrient solutions containing a more soluble Ca source than the sources used by St. John et al. (2001 and 2003). However, the leaf Ca concentration of all grasses grown on calcareous sand was high ($> 10.5 \text{ g}\cdot\text{kg}^{-1}$) according to Mills and Jones (1996) even in grasses that received no extra Ca fertilization. The calcareous sand alone was supplying more than enough Ca for proper growth.

Silica sand samples had very low exchangeable cation concentrations, but yet leaf concentrations of Ca and Mg were adequate to high. This is best explained due to the fact that the cation solutions were applied weekly. It is probable that the grasses may have been receiving most of their cation requirements from the soil solution phase and not the exchangeable fraction.

This research demonstrates several limitations of applying the BCSR theory to sand-based turfgrass systems. Firstly, it is possible, that soil sample can have a correct or high cation saturation percentage, but still be deficient in one or several nutrients. Potassium saturation percentages of silica sand samples were very high, but the actual soil extractable level and leaf concentrations were deficient.

The second fault of using the BCSR theory for sand-based putting greens shown in this research has to do with the nature of how the ratios and percentages are calculated. The BCSR theory is based entirely on the extractable cation concentrations and the CEC. But many times, the sands used for putting green construction have very low CEC and low concentrations of extractable cations. There will be great variability and a high probability for error, when cation percentages and ratios are created from very small numbers. The silica

sand samples had such low exchangeable cations and low ECEC values that the cation ratios were misleading. The Ca:K ratio ranged from 1:1 to 2:1, which according to the BCSR theory would result in a recommendation of supplemental Ca applications to bring the ratio back closer to 13:1 Ca:K. But, the leaf Ca concentrations of silica sand were well above deficiency levels and the leaf K levels were low, which would mean that K rather than Ca should be applied.

The problem with calculating cation ratios and percentages is even further complicated by different soil analysis techniques. Many soil testing techniques will dissolve carbonates and sulfates, which will increase the levels of exchangeable cations, like Ca or Mg. Calcium carbonates were dissolved during the analysis of the calcareous sand samples, resulting in Ca saturation percentages all greater than 95% saturation. Therefore, the Ca:Mg and Ca:K ratios were very high, >20:1 and >64:1, respectively. With soil-based rootzone media that is high in clay and organic matter, this dissolution problem may not greatly affect the cation ratios or percentages. But with low CEC calcareous sand, carbonate dissolution can greatly affect the cation ratios and saturation percentages of low-CEC calcareous sands. Both complications resulting from low CEC sands and from calcareous media probably resulted in the differences between the applied treatment cation ratios and the measured cation ratios of the different sands in this study.

Cation ratios and saturation percentages become widely variable and erroneous when using low CEC sand media. Moreover, the ratios become even more misleading when the rootzone media is calcareous. Therefore, the BCSR theory of soil test interpretation should not be used as the sole factor in developing a turfgrass fertility program for sand-based rootzones that have either a low CEC or are calcareous.

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Table 1. Cation saturation percentages and cation ratios of the current BCSR theory and an extension of cation ratios based upon Graham's (1959) saturation percentages.

Cation Equivalent Ratio	Exact Cation Saturation Percentages †	Exact Cation Ratios †	Current Cation Saturation Percentages ^ϕ	Possible Range of Cation Ratios
Ca:Mg	Ca 65% Mg 10%	6.5:1	Ca 65-85% Mg 6-12%	5.4:1 – 14:1
Ca:K	Ca 65% K 5%	13:1	Ca 65-85% K 2-5%	13:1 – 42.5
Mg:K	Mg 10% K 5%	2:1	Mg 6-12% K 2-5%	1.2:1 – 6:1

† Percentages and ratios originally proposed by Bear and Toth (1948).

^ϕ Current range of saturation percentages proposed by Graham (1959).

Table 2: List of treatments as ideal saturation percentages and actual nutrient concentrations within each solution used in the greenhouse mixtures experiments.

Treatment	<u>Ca</u>	<u>Mg</u>	<u>K</u>	<u>H</u>	<u>Ca</u>	<u>Mg</u>	<u>K</u>	<u>H</u>
	-----%				-----mg•L ⁻¹ -----			
1	0	0	80	20	0.0	0.0	312.8	2.0
2	0	0	95	5	0.0	0.0	371.4	0.5
3	0	40	40	20	0.0	48.6	156.4	2.0
4	0	47.5	47.5	5	0.0	57.7	185.7	0.5
5	0	80	0	20	0.0	97.2	0.0	2.0
6	0	95	0	5	0.0	115.4	0.0	0.5
7	26.67	26.67	26.67	20	53.4	32.4	104.3	2.0
8	31.67	31.67	31.67	5	63.5	38.5	123.8	0.5
9	40	0	40	20	80.2	0.0	156.4	2.0
10	40	40	0	20	80.2	48.6	0.0	2.0
11	47.5	0	47.5	5	95.2	0.0	185.7	0.5
12	47.5	47.5	0	5	95.2	57.7	0.0	0.5
13	65	6	1	28	130.3	7.3	3.9	2.8
14	65	6	5	24	130.3	7.3	19.5	2.4
15	65	12	1	22	130.3	14.6	3.9	2.2
16	65	12	5	18	130.3	14.6	19.5	1.8
17	75	9	3	13	150.3	10.9	11.7	1.3
18	80	0	0	20	160.3	0.0	0.0	2.0
19	85	6	1	8	170.3	7.3	3.9	0.8
20	85	6	5	4	170.3	7.3	19.5	0.4
21	85	12	1	2	170.3	14.6	3.9	0.2
22	85	12	3	0	170.3	14.6	11.7	0.0
23	95	0	0	5	190.4	0.0	0.0	0.5
24	95	5	0	0	190.4	6.1	0.0	0.0
25	0	0	0	0	0.0	0.0	0.0	0.0
26	5	95	0	0	10.0	115.4	0.0	0.0
27	99	0	1	0	198.4	0.0	3.9	0.0
28	1	0	99	0	2.0	0.0	387.1	0.0

Figure 1: Three and two dimensional representations of the treatments used in this study (gray) compared to the space occupied by the 'ideal soil' according to the BCSR theory (black). The axis' represent the percent saturation of the cation exchange sites from 0 – 100%. In the two dimensional plot on the right, H would be the Z-axis coming out of the page and is not shown.

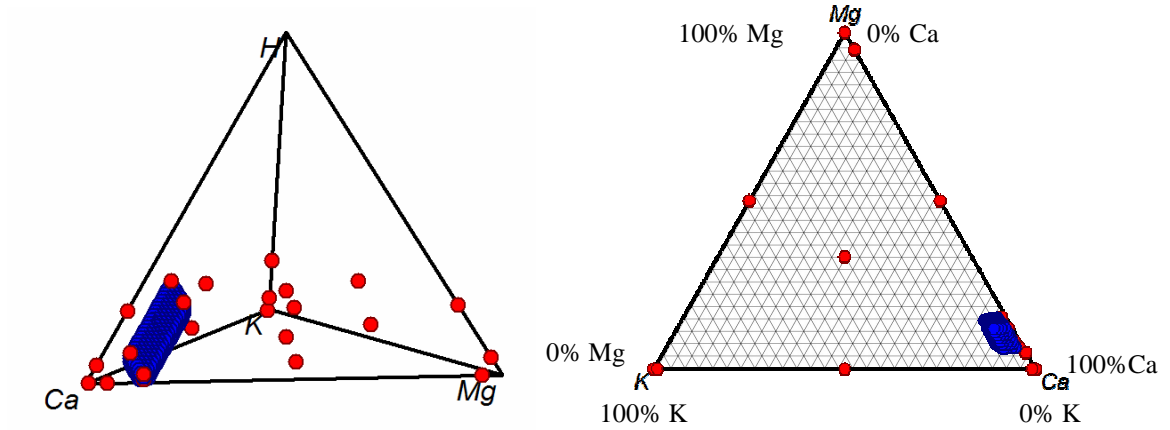


Table 3. Type 3 tests of fixed effects of leaf Ca concentration generated by using the Mixed Procedure of Statistical Analysis Software.

Effect	Num df	Den df	F Value	Pr >F
Sand	1	1	17.24	0.1505
Treatment	27	27.1	3.47	0.0009
Sand*Treatment	27	27.9	1.24	0.2851
Date	2	2.01	1.90	0.3440
Sand*Date	2	1	8.78	0.2321
Treatment*Date	54	54.6	1.21	0.2443
Sand*Treatment*Date	54	53	1.13	0.3305

Table 4. Leaf Ca concentrations of creeping bentgrass fertilized at different basic cation saturation ratios. Data are averaged over sand type and sampling time. The first 9 treatments listed in the table have an ideal basic cation saturation ratio according to the BCSR theory. Each of the remaining treatments was compared to the average of the 9 'ideal' treatments by using contrast statements. Data averaged over 3 sets of clippings taken at 1, 6, and 12 weeks after treatment initiation.

Trt	Treatment Cation Percentages				Calcareous Sand	Silica Sand
	Ca	Mg	K	H	Leaf Ca g•kg ⁻¹	Leaf Ca g•kg ⁻¹
13	65	6	1	28	14.25	7.63
14	65	6	5	24	15.16	9.06
15	65	12	1	22	15.23	9.30
16	65	12	5	18	15.33	10.37
17	75	9	3	13	15.08	11.53
19	85	6	1	8	14.50	10.69
20	85	6	5	4	14.38	10.50
21	85	12	1	2	14.42	10.17
22	85	12	3	0	14.96	10.92
1	0	0	80	20	10.49*	10.98*
2	0	0	95	5	10.52*	11.67*
3	0	40	40	20	11.88	13.70*
4	0	47.5	47.5	5	11.47*	12.96*
5	0	80	0	20	13.22	13.11
6	0	95	0	5	12.82	14.53*
7	26.67	26.67	26.67	20	12.50	14.19*
8	31.67	31.67	31.67	5	12.36	13.74*
9	40	0	40	20	12.51*	14.36*
10	40	40	0	20	13.47	12.89*
11	47.5	0	47.5	5	12.36*	12.27
12	47.5	47.5	0	5	14.46	13.05
18	80	0	0	20	15.51	13.44
23	95	0	0	5	15.73	14.16
24	95	5	0	0	15.76	14.07
25	0	0	0	0	12.84	11.38*
26	5	95	0	0	13.23	11.50
27	99	0	1	0	14.91	13.43
28	1	0	99	0	11.74*	9.80*
Creeping bentgrass Sufficiency Ranges†					5.0 – 7.5	
Creeping bentgrass Survey Ranges†					2.1 – 5.0	

* Indicates that this treatment is different from the average of the 9 treatments that have 'ideal' basic cation saturation ratios at the 0.05 level.

† Sufficiency Ranges and Survey Ranges for tissue nutrient content of creeping bentgrass. The limits for the Sufficiency Ranges have been more precisely defined over a variety of different growing conditions compared to the limits of the Survey Ranges (Mills and Jones, 1996).

Table 5. Type 3 tests of fixed effects of leaf Mg concentration generated by using the mixed procedure of Statistical Analysis Software.

Effect	Num df	Den df	F Value	Pr >F
Sand	1	1	0.00	0.9632
Treatment	27	27	6.19	<.0001
Sand*Treatment	27	27.1	3.31	0.0014
Date	2	2.12	15.85	0.0532
Sand*Date	2	2	0.85	0.5410
Treatment*Date	54	51	6.83	<.0001
Sand*Treatment*Date	54	57.9	2.07	0.0036

Table 6. Leaf Mg concentrations of creeping bentgrass grown on either calcareous or silica sand fertilized at different basic cation saturation ratios. The first 9 treatments listed in the table have an ideal basic cation saturation ratio according to the BCSR theory. Each of the remaining treatments was compared to the average of the 9 'ideal' treatments by using contrast statements. Clippings are from weeks 1, 6, and 12 weeks after treatment initiation.

Trt	Ca	Treatment Cation Percentages			Date	Calcareous Sand	Silica Sand
		Mg	K	H		Leaf Mg g•kg ⁻¹	Leaf Mg g•kg ⁻¹
13	65	6	1	28	1	2.61	2.81
					6	3.06	2.87
					12	3.00	2.51
14	65	6	5	24	1	2.60	2.65
					6	2.98	2.63
					12	2.96	2.30
15	65	12	1	22	1	2.61	2.81
					6	2.99	3.04
					12	2.98	2.81
16	65	12	5	18	1	2.66	2.77
					6	3.03	2.94
					12	3.10	2.56
17	75	9	3	13	1	2.73	2.90
					6	3.13	2.96
					12	3.10	2.46
19	85	6	1	8	1	2.64	2.84
					6	3.04	2.93
					12	2.96	2.59
20	85	6	5	4	1	2.57	2.63
					6	2.97	2.80
					12	2.82	2.41
21	85	12	1	2	1	2.61	2.76
					6	3.15	3.16
					12	3.01	2.92
22	85	12	3	0	1	2.56	2.82
					6	2.89	3.09
					12	3.14	2.89
1	0	0	80	20	1	2.43	2.32
					6	2.38	1.71*
					12	2.32*	1.50*
2	0	0	95	5	1	2.33	2.45
					6	2.38	1.67*
					12	2.34	1.42*
3	0	40	40	20	1	2.53	2.89
					6	2.80	2.85
					12	2.86	2.87

Table 6. Continued.

Trt	Ca	Treatment Cation Percentages		H	Date	Calcareous Sand	Silica Sand
		Mg	K			Leaf Mg	Leaf Mg
						g•kg ⁻¹	g•kg ⁻¹
4	0	47.5	47.5	5	1	2.60	2.93
					6	2.92	2.88
					12	2.88	2.97
5	0	80	0	20	1	2.97	3.61
					6	3.91*	4.92*
					12	4.38*	5.29*
6	0	95	0	5	1	3.06	4.37*
					6	4.07*	5.50*
					12	4.43*	5.85*
7	26.67	26.67	26.67	20	1	2.44	2.65
					6	2.84	2.86
					12	2.92	2.95
8	31.67	31.67	31.67	5	1	2.46	2.71
					6	2.72	2.68
					12	2.75	2.90
9	40	0	40	20	1	2.40	2.21
					6	2.42*	1.84*
					12	2.45	1.63
10	40	40	0	20	1	2.83	3.37
					6	3.33	3.98*
					12	3.60	3.84*
11	47.5	0	47.5	5	1	2.36	2.46
					6	2.31*	1.83*
					12	2.16*	1.62*
12	47.5	47.5	0	5	1	2.79	3.72*
					6	3.40	4.27*
					12	3.49	4.22*
18	80	0	0	20	1	2.67	2.65
					6	2.95	2.40
					12	3.02	2.09
23	95	0	0	5	1	2.73	2.48
					6	2.83	2.40
					12	2.81	2.10
24	95	5	0	0	1	2.63	2.72
					6	3.06	2.75
					12	3.11	2.37
25	0	0	0	0	1	2.56	2.32
					6	3.07	1.87*
					12	2.97	1.90*
26	5	95	0	0	1	2.99	4.02*
					6	3.91*	5.54*
					12	4.14	5.93*
27	99	0	1	0	1	2.57	2.34
					6	2.89	2.28
					12	2.79	1.87*
28	1	0	99	0	1	2.45	2.42
					6	2.22*	1.72*
					12	2.11*	1.49*
Creeping bentgrass Sufficiency Ranges†						2.5 – 3.0	
Creeping bentgrass Survey Ranges†						0.9 – 2.2	

* Indicates that this treatment is different from the average of the 9 treatments that have 'ideal' basic cation saturation ratios at the 0.05 level.

† Sufficiency Ranges and Survey Ranges for tissue nutrient content of creeping bentgrass. The limits for the Sufficiency Ranges have been more precisely defined over a variety of different growing conditions compared to the limits of the Survey Ranges (Mills and Jones, 1996).

Table 7. Type 3 tests of fixed effects of leaf K concentration generated by using the mixed procedure of Statistical Analysis Software.

Effect	Num df	Den df	F Value	Pr >F
Sand	1	1	1.13	0.4811
Treatment	27	27	18.54	<.0001
Sand*Treatment	27	27	23.40	<.0001
Date	2	2	0.90	0.5250
Sand*Date	2	2	0.94	0.5143
Treatment*Date	54	52.4	3.60	<.0001
Sand*Treatment*Date	54	52.2	0.95	0.5715

Table 8. Leaf K concentrations of creeping bentgrass grown on either calcareous or silica sand fertilized at different basic cation saturation ratios. The first 9 treatments listed in the table have an ideal basic cation saturation ratio according to the BCSR theory. Each of the remaining treatments was compared to the average of the 9 'ideal' treatments by using orthogonal contrasts. Data averaged over 3 sets of clippings taken at 1, 6, and 12 weeks after treatment initiation.

Trt	Treatment Cation Percentages				H	Calcareous Sand	Silica Sand
	Ca	Mg	K	Leaf K		Leaf K	
					g•kg ⁻¹	g•kg ⁻¹	
13	65	6	1	28	9.52	4.05	
14	65	6	5	24	9.78	5.77	
15	65	12	1	22	9.08	4.68	
16	65	12	5	18	9.43	5.55	
17	75	9	3	13	9.18	4.60	
19	85	6	1	8	8.72	4.77	
20	85	6	5	4	9.49	5.64	
21	85	12	1	2	8.94	4.34	
22	85	12	3	0	9.29	5.18	
1	0	0	80	20	16.47*	20.82*	
2	0	0	95	5	17.00*	21.36*	
3	0	40	40	20	13.49	15.32*	
4	0	47.5	47.5	5	14.49*	16.99*	
5	0	80	0	20	9.11	4.70	
6	0	95	0	5	8.29	4.34	
7	26.67	26.67	26.67	20	13.05	12.60*	
8	31.67	31.67	31.67	5	13.05	13.09*	
9	40	0	40	20	13.95	16.00*	
10	40	40	0	20	8.04	4.06	
11	47.5	0	47.5	5	14.12	17.00*	
12	47.5	47.5	0	5	8.28	3.94	
18	80	0	0	20	8.17	4.20	
23	95	0	0	5	8.37	4.20	
24	95	5	0	0	8.17	4.11	
25	0	0	0	0	8.11	4.36	
26	5	95	0	0	8.71	3.87	
27	99	0	1	0	9.23	4.60	
28	1	0	99	0	16.78*	20.39*	
Creeping bentgrass Sufficiency Ranges†						22 – 26	
Creeping bentgrass Survey Ranges†						8.6 – 26	

* Indicates that this treatment is different from the average of the 9 treatments that have 'ideal' basic cation saturation ratios at the 0.05 level.

† Sufficiency Ranges and Survey Ranges for tissue nutrient content of creeping bentgrass. The limits for the Sufficiency Ranges have been more precisely defined over a variety of different growing conditions compared to the limits of the Survey Ranges (Mills and Jones, 1996).

Table 9. Average measured cation saturation percentages of calcareous or silica sands samples from pots established with creeping bentgrass receiving various cation nutrient solutions.

Trt	Treatments			Calcareous Sand			Silica Sand		
	Ca	Mg	K	%Ca	%Mg	%K	%Ca	%Mg	%K
1	0	0	80	96	3	1.2	34	0	66
2	0	0	95	96	2	1.4	33	1	65
3	0	40	40	97	2	0.2	68	5	28
4	0	47.5	47.5	96	3	0.7	40	7	52
5	0	80	0	96	4	0.5	21	7	73
6	0	95	0	95	5	0.7	53	22	26
7	26.67	26.67	26.67	97	3	0.6	47	5	48
8	31.67	31.67	31.67	97	3	0.7	57	5	38
9	40	0	40	97	2	1.1	58	0	42
10	40	40	0	97	3	0.8	53	6	41
11	47.5	0	47.5	97	2	1.0	54	0	46
12	47.5	47.5	0	97	3	0.4	49	7	44
13	65	6	1	98	2	0.4	32	1	68
14	65	6	5	99	2	0.5	42	1	57
15	65	12	1	98	2	0.3	66	2	32
16	65	12	5	97	2	0.8	33	3	65
17	75	9	3	97	2	0.7	52	2	46
18	80	0	0	98	2	0.5	61	1	38
19	85	6	1	97	2	0.4	37	3	60
20	85	6	5	97	2	0.8	57	3	40
21	85	12	1	98	2	0.6	22	10	68
22	85	12	3	97	2	0.5	53	2	45
23	95	0	0	98	2	0.5	59	0	42
24	95	5	0	97	2	0.6	46	4	51
25	0	0	0	97	2	0.7	40	0	59
26	5	95	0	95	4	0.5	20	20	60
27	99	0	1	97	2	0.5	47	0	53
28	1	0	99	96	2	1.5	50	3	48
'Ideal Soil' Saturation Percentages				65-85%	6-12%	1-5%	65-85%	6-12%	1-5%

Table 10. Average cation ratios measured from calcareous or silica sand samples from pots established with creeping bentgrass receiving various cation nutrient solutions.

Trt	Treatments				Calcareous Sand			Silica Sand		
	Ca	Mg	K	Ca	Ca:Mg	Ca:K	Mg:K	Ca:Mg	Ca:K	Mg:K
1	0	0	80	0	38:1	81:1	2:1	n/a [†]	1:1	n/a
2	0	0	95	0	41:1	70:1	2:1	23:1	1:1	0.0:1
3	0	40	40	0	37:1	401:1	11:1	14:1	2:1	0.2:1
4	0	47.5	47.5	0	33:1	131:1	4:1	6:1	1:1	0.1:1
5	0	80	0	0	25:1	184:1	7:1	3:1	0:1	0.1:1
6	0	95	0	0	20:1	145:1	7:1	2:1	2:1	0.9:1
7	26.67	26.67	26.67	26.67	37:1	162:1	4:1	9:1	1:1	0.1:1
8	31.67	31.67	31.67	31.67	39:1	142:1	4:1	11:1	1:1	0.1:1
9	40	0	40	40	48:1	89:1	2:1	n/a	1:1	n/a
10	40	40	0	40	37:1	126:1	3:1	9:1	1:1	0.1:1
11	47.5	0	47.5	47.5	49:1	102:1	2:1	220:1	1:1	0.0:1
12	47.5	47.5	0	47.5	32:1	263:1	8:1	7:1	1:1	0.2:1
13	65	6	1	65	50:1	240:1	5:1	50:1	0:1	0.0:1
14	65	6	5	65	51:1	204:1	4:1	47:1	1:1	0.0:1
15	65	12	1	65	52:1	362:1	7:1	42:1	2:1	0.0:1
16	65	12	5	65	45:1	121:1	3:1	12:1	1:1	0.0:1
17	75	9	3	75	46:1	138:1	3:1	35:1	1:1	0.0:1
18	80	0	0	80	48:1	206:1	4:1	52:1	2:1	0.0:1
19	85	6	1	85	46:1	222:1	5:1	13:1	1:1	0.0:1
20	85	6	5	85	51:1	129:1	3:1	22:1	1:1	0.1:1
21	85	12	1	85	51:1	165:1	3:1	2:1	0:1	0.1:1
22	85	12	3	85	47:1	189:1	4:1	23:1	1:1	0.1:1
23	95	0	0	95	53:1	190:1	4:1	n/a	1:1	n/a
24	95	5	0	95	48:1	158:1	3:1	12:1	1:1	0.1:1
25	0	0	0	0	46:1	132:1	3:1	146:1	1:1	0.0:1
26	5	95	0	5	22:1	196:1	9:1	1:1	0:1	0.3:1
27	99	0	1	99	49:1	185:1	4:1	n/a	1:1	n/a
28	1	0	99	1	43:1	64:1	1:1	19:1	1:1	0.1:1
'Ideal Soil' Cation ratios					6:5:1	13:1	2:1	6.5:1	13:1	2:1

[†] n/a. Not able to be calculated since Mg percent saturation was 0 for these treatments.

Table 11. Soil extractable cations from calcareous and silica sands. Soil test designations are also listed.

Trt	Treatments				Calcareous			Silica		
	Ca	Mg	K	H	Ca	Mg	K	Ca	Mg	K
	% of CEC				-----mg•kg ⁻¹ -----					
1	65	6	1	28	1919.50	30.46	45.58	5.54	20.81	0.00
2	65	6	5	24	1943.93	28.37	54.39	4.77	23.21	0.13
3	65	12	1	22	1824.52	29.89	8.84	3.71	8.47	0.19
4	65	12	5	18	1789.00	33.43	28.20	6.93	17.61	0.75
5	75	9	3	13	1968.72	46.96	20.81	5.19	33.26	0.77
6	85	6	1	8	1881.34	56.11	25.86	2.43	9.27	0.26
7	85	6	5	4	1905.20	31.15	22.83	6.83	18.89	0.29
8	85	12	1	2	1908.93	29.59	28.07	6.34	16.07	0.69
9	85	12	3	0	1904.71	23.44	41.83	3.45	8.89	0.00
10	0	0	80	20	2025.36	32.35	31.14	6.48	15.94	0.60
11	0	0	95	5	1896.11	23.08	36.42	7.36	22.97	0.04
12	0	40	40	20	1794.51	32.96	13.41	6.80	16.65	0.58
13	0	47.5	47.5	5	1884.32	22.44	16.33	7.13	25.77	0.07
14	0	80	0	20	1885.42	22.21	19.14	6.20	19.20	0.08
15	0	95	0	5	1836.06	21.06	10.19	5.30	8.57	0.09
16	26.67	26.67	26.67	20	1981.81	26.48	31.62	8.53	30.31	0.30
17	31.67	31.67	31.67	5	1954.33	25.27	27.95	8.84	18.07	0.16
18	40	0	40	20	1793.41	22.59	17.84	6.21	10.93	0.08
19	40	40	0	20	1965.61	25.26	17.89	7.89	21.10	0.29
20	47.5	0	47.5	5	2010.21	23.78	30.44	6.74	15.51	0.27
21	47.5	47.5	0	5	2012.16	23.62	24.10	5.23	24.38	1.64
22	80	0	0	20	1894.47	23.90	19.82	6.35	18.72	0.16
23	95	0	0	5	1931.06	21.99	20.47	6.90	17.13	0.00
24	95	5	0	0	2022.76	25.29	25.33	6.85	16.10	0.39
25	0	0	0	0	1995.59	26.33	29.33	5.03	18.07	0.02
26	5	95	0	0	1850.98	50.25	18.09	3.22	15.91	0.30
27	99	0	1	0	1907.66	23.22	19.80	8.99	22.53	0.00
28	1	0	99	0	1971.29	27.35	60.04	5.58	21.33	0.22

Soil Test Designations mg•kg ⁻¹			
	Ca [‡]	K [†]	Mg [‡]
Low	<250	41-175	<20
Very Low		<40	

[†] Values taken from Christians (2004). K concentrations less than 40 mg•kg⁻¹ are classified as having 'very low' extractable K. K concentrations between 41 and 175 mg•kg⁻¹ are classified as having 'low' extractable K.

[‡] Values taken from Puhalla, et al., (1999). Ca concentrations less than 250 mg•kg⁻¹ are classified as having 'low' extractable Ca. Mg concentrations less than 20 mg•kg⁻¹ are classified as having 'low' extractable Mg.

General Conclusions

The presence of CaCO_3 can greatly affect the results of various soil testing techniques for measuring exchangeable basic cations and for calculating effective cation exchange capacities (ECEC). Of the procedures examined in this research, the NH_4OAc pH 8.1 appears to be the best extractant for measuring exchangeable cations from calcareous or gypsiferous sand samples. The NH_4OAc pH 8.1 technique had the lowest rates of dissolution of CaCO_3 , but it still dissolved appreciable quantities of CaCO_3 found in this media. Therefore, calculating an ECEC by summation of exchangeable cations measured from any of the procedures evaluated in this research, including NH_4OAc pH 8.1 is not advised for samples from calcareous or gypsiferous sands. To accurately measure CEC of calcareous or gypsiferous sand samples, a double extraction technique should be used.

Sands used for putting green or sports field construction often have a very low CEC. Measuring small differences in CEC by using different soil-testing techniques may not provide useful information to the turfgrass manager and may result in erroneous fertilizer recommendations. It is not necessarily important that a turf manager knows if the root zone media has a CEC 1 or 7. But, it is more important for the turf manager to understand the limitations of low CEC media when developing a fertility program by using small, frequent applications of fertilizers, known as spoon-feeding, and using slowly-available fertilizer sources. However, using more complicated double extraction techniques for measuring small differences in CEC can be important when conducting research or trying to compare rootzone media from different locations. And, accurate CEC measurements using double extraction techniques should also be used when evaluating the statements of consultants and

specialty fertilizer companies that claim to have products which have the ability to modify the CEC of a soil.

From this research, it appears that creeping bentgrass can tolerate a wide range of basic cations in soil solution. We were unable to determine an exact set of cation ratios for creeping bentgrass established on sands. But, many problems applying the BCSR theory to sand-based greens were noted.

This research demonstrated one of the problems of using the BCSR theory, in that it is possible to have nutrient deficiencies even though the cations exist in the correct or even high percentages of the CEC. Silica sand samples had high K cation saturation percentages, which under the BCSR theory of soil test interpretation would call for additional Ca. But, the soil extractable K and leaf tissue K concentrations were deficient within many treatments indicating a need for additional K. Although no growth or quality issues were observed within the 12 weeks of these experiments, it is probable that problems would eventually occur, if these conditions were to continue.

Using the BCSR theory for low CEC sand-based media is further complicated when sands have low CEC values and exchangeable cation concentrations. Cation ratios and percentages created from these low numbers can vary greatly and can easily change. Furthermore, ratios and percentages are going to be erroneous when created from values generated from a soil testing method that dissolves carbonates or sulfates.

For high sand, low CEC rootzones used for putting greens and sports fields, the BCSR theory does not appear to be applicable and should not be used alone to make fertility recommendations.

APPENDIX 1

TURFGRASS TISSUE NUTRIENT RANGES

Table 1. Sufficiency Ranges for tissue nutrient content of creeping bentgrass (*Agrostis palustris*), Bermudagrass (*Cynodon dactylon*), Perennial ryegrass (*Lolium perenne*), and St. Augustinegrass (*Stenotaphrum secundatum*). And Survey Ranges for Kentucky bluegrass (*Poa pratensis*), Creeping bentgrass, Tall Fescue (*Festuca arundinacea*), and Zoysiagrass (*Zoysia japonica* 'El Toro'). The limits for the Sufficiency Ranges have been more precisely defined over a variety of different growing conditions compared to the limits of the Survey Ranges.[†]

	Sufficiency and Survey Ranges					
	Ca	N	P	K	Mg	Mn
	g·kg ⁻¹					mg·kg ⁻¹
	Sufficiency Ranges					
Creeping bentgrass	5.0 – 7.5	45 – 60	3.0 – 6.0	22 – 26	2.5 – 3.0	50 - 100
Bermudagrass	3.5 – 10	23 – 50	1.5 – 5.0	10 – 40	1.3 – 5.0	25 - 300
Perennial ryegrass	2.5 – 5.1	33 – 51	3.5 – 5.5	20 – 34	1.6 – 3.2	30 - 73
St. Augustinegrass	3.0 – 5.0	19 – 30	2.0 – 5.0	25 – 40	1.5 – 2.5	40 - 250
	Survey Ranges					
Kentucky bluegrass	2.7 – 5.8	25 - 51	2.7 – 4.0	17 - 30	1.3 – 1.6	30 - 160
Creeping bentgrass	2.1 – 5.0	24 – 83	2.0 – 5.5	8.6 – 26	0.9 – 2.2	30 -160
Tall Fescue	4.0 – 4.5	34 – 47	3.4 – 5.0	30 - 40	2.4 – 2.9	54 -74
Zoysiagrass	4.2 – 5.2	19 – 22	1.8 – 2.6	11 – 15	1.3 – 1.5	26 - 31

[†] Values from Mills, H.A. and J.B. Jones, Jr.. 1996. Plant Analysis Handbook II. Micromacro Publishing, Athens, GA. p. 347 - 353.

APPENDIX 2
SOIL TEST RANGES

Table 1. Soil test designations for 10 different nutrients in turfgrass soils.

Nutrient	Pounds per Acre	mg·kg ⁻¹ ‡	Designation
Phosphorus ^Ω	<10	<5	Very Low
	12 – 20	6 – 10	Low
	20 – 40	10 – 20	Adequate
	>40	>20	High
Potassium ^Ω	<80	<40	Very Low
	81 – 350	41 – 175	Low
	350 – 500	175 – 250	Adequate
	>500	>250	High
Calcium [†]	<500	<250	Low
Magnesium [†]	<40	<20	Low
Sulfur [†]	<15	<7.5	Low
	15-50	8 – 25	Medium
	>50	>25	High
Boron [†]	<0.5	<0.25	Low
	0.5 – 1.5	0.25 – 0.75	Medium
	>1.5	>0.75	High
Copper [†]	<0.5	<0.25	Low
	0.5 – 5	0.25 – 5	Medium
	>5	>2.5	High
Iron [†]	<15	<7.5	Low
	15 – 120	7.5 – 60	Medium
	>120	>60	High
Manganese [†]	<10	<5	Low
	10 – 50	5 – 25	Medium
	>50	>25	High
Zinc [†]	<2	<1	Low
	2 – 5	1 – 2.5	Medium
	>5	>2.5	High

^Ω Values taken from Christians, N.E. 1998. Fundamentals of turfgrass management. Ann Arbor Press, Inc. Chelsea, MI. p. 109

[†] Values taken from Puhalla, J., J. Krans, and M. Goatly. 1999. Sports fields: A manual for design, construction, and maintenance of sports fields. Ann Arbor Press, Chelsea, MI. p. 41.

[‡] Assuming that an acre-furrow slice weighs 2 million pounds.

Table 2. Typical soil test SLAN sufficiency ranges for macronutrients using common extractants.

SLAN RANGES					
Nutrient	Soil [†]	Medium sufficiency range (ppm)	Extractant		
Phosphorus	All	15-30	Mehlich I		
	All	26-54	Mehlich II		
	All	15-30	Bray P1		
	All	12-28	Olsen		
	All	10-20	Morgan		
Potassium	Sands	75-175	NH ₄ OAc (pH7.0)		
	Others	100-235	NH ₄ OAc (pH7.0)		
	Sands	50-116	Mehlich III		
	Others	75-176	Mehlich III		
	Sands	50-100	Mehlich I		
	Others	90-200	Mehlich I		
	All	155-312	Olsen		
	All	120-174	Morgan		
Calcium	All	200-350 [‡]	Mehlich I		
	All	500-750 [‡]	Mehlich III		
	All	500-750 [‡]	NH ₄ OAc (pH7.0)		
	All	500-750 [‡]	Morgan		
	Sands	30-60	Mehlich I		
	Others	50-100	Mehlich I		
	Sands	60-120	Mehlich III		
	Others	70-140	Mehlich III		
	Sands	100-200	NH ₄ OAc (pH7.0)		
	Others	140-250	NH ₄ OAc (pH7.0)		
	All	>100	Morgan		
	All	10-20	Ca(H ₂ PO ₄) ₂		
	All	30-60	NH ₄ OAc (pH7.0)		
All	15-40	Mehlich III			

Note. The values in this table are from many sources and are typical. A particular laboratory may vary from these rankings for local soil conditions.

*Soils that have high CEC (>15 cmol/kg) may exhibit a higher "medium" sufficiency range. The "medium" sufficiency range in this table is based on sands or other soils with CEC <15 cmol/kg.

[†]On sites receiving irrigation water high in sodium, the upper level of the sufficiency range should be used as a guideline (for example, for Mehlich III, this would be 750ppm calcium or higher).

Values from Carrow, R.N., L. Stowell, W. Gelernter, S. Davis; R.R. Duncan, and J. Skorulski. 2004. Clarifying soil testing: III. SLAN sufficiency ranges and recommendations. Golf Course Management, Jan 2004 194-198.

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